F-111 Sole Operator Program: Maintaining the Structural Integrity of an Ageing Fighter Aircraft

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Introduction

The F-111 is a dual-seat, supersonic, variable-geometry-wing strike aircraft that has enjoyed RAAF and USAF service for the last 30 years. Approximately 550 aircraft were built between 1964 and 1973, with model variants from F-111A to F-111F. RAAF operations commenced in 1973 with the purchase of 24 F-111C aircraft and are planned to continue to 2020. Due to the age of the fleet and its changed circumstances following the retirement of the USAF F-111 fleets, a special program was initiated by the RAAF [1], to step back and take a fresh, holistic look at its F-111 aircraft structural integrity (ASI) management. It was titled the 'F-111 Sole Operator Program' and the aim was to ensure that all the required capabilities and data were in place to support the structural integrity of the aircraft to 2020.

The Sole Operator Program (SOP) sits in a framework of broader RAAF initiatives to ensure the supportability of all F-111 systems to the planned withdrawal date. This paper describes both the F-111 SOP and the broader RAAF initiatives on F-111 structural integrity. It is a comprehensive program tailored to management by safety-by-inspection, and encompasses identification of all potential structural degradation sites and all relevant degradation mechanisms, analysis of fatigue and corrosion growth rates, developing and characterising NDI techniques, and developing repairs, modifications and part substitution technologies. Corrosion prevention and control is also a key element of the program.

The F-111 SOP includes extending existing capabilities through applied research to address particular F-111 ASI issues associated with its special materials such as D6ac steel, 7079 T651 aluminium alloy and bonded aluminium honeycomb panels. Two highlights of this research (viz. rework shape optimisation and fibre composite replacement panels) are presented here, following an overview of the overall SOP.

RAAF F-111 Fleet

The RAAF F-111 fleet currently comprises 13 F-111C, 4 RF-111C (C models modified for the reconnaissance role), 4 F-111A (attrition replacements) and 14 F-111G (used ex-USAF aircraft purchased to extend the fleet). The F-111 role in RAAF service is strategic strike and reconnaissance. With near 30 years of operations completed, most RAAF aircraft have

Paper presented at the RTO AVT Specialists' Meeting on "Life Management Techniques for Ageing Air Vehicles", held in Manchester, United Kingdom, 8-11 October 2001, and published in RTO-MP-079(II).

completed between 5,000 and 7,500 AFHRS[1]. On withdrawal, RAAF aircraft will have experienced almost 50 years service and 10,000 AFHRS. The F-111 has enjoyed an excellent safety record in RAAF service and is highly regarded with respect to its military capability and flexibility.

Specifically, the F-111 is managed on a Safety by Inspection (SBI) basis, which is underpinned by the Durability and Damage Tolerance philosophy. This is implemented through the completion of Durability and Damage Tolerance Analyses (DADTAs) for the critical structural locations, or DADTA Items (DIs). The RAAF has implemented a dedicated DADTA program accounting for the structural differences and based on RAAF F-111 usage.

Capability Options Study

In the mid 1990s the capability planning area of the RAAF carried out a study of F-111 supportability and replacement options. The costs of supporting all F-111 systems were accounted. The study concluded that the continued operation of the F-111 was clearly the best option to sustain at a reasonable cost the strike capability for Australia's defence.

Impact of US Fleet Retirement

The RAAF relied heavily on the USAF and the OEM (Lockheed Martin, LMAero, Fort Worth) for F-111 ASI support. The USAF had significantly larger fleets of F-111s and their fleet leaders were generally at higher hours (~ 7,500 AFHRS) than the RAAF fleet leaders (~ 6,000 AFHRS, before the G model acquisition). The USAF generally found the problems first and developed engineering solutions in conjunction with the OEM, which were made available to the RAAF. The RAAF also directly tasked the OEM for support on RAAF-specific F-111 ASI problems. A good example of this is the cold work modification of the overwing longerons which was developed by LMAero for the USAF and is currently being applied to the RAAF fleet.

With the withdrawal of the last USAF F-111 fleet in 1998, the RAAF became the sole operator of the aircraft type and it would not be long before the RAAF fleet leaders overtook where the USAF fleet leaders had finished. It was also recognised to be not viable for the small RAAF fleet to sustain the full OEM support for the F-111.

Another significant impact of the USAF fleet retirement was the closure of their F-111 maintenance facilities that the RAAF previously had access to. These included the cold proof load test[2] (CPLT) facility and the bonded panel repair and rebuild facility. In short, with USAF involvement, the RAAF was able to assure airworthiness and good aircraft availability without large investments in support infrastructure.

Structural Management Initiatives

Spares Purchase

With the winding back of OEM support, the RAAF completed a dedicated program to identify LOT spares requirements, and to make purchases where continued supplies could not be guaranteed. The purchases not only included specific manufacture runs where necessary, but also included the purchase of ex-USAF spares inventories. Further, with many serviceable USAF aircraft retired, a number of aircraft and components have been earmarked as future spares sources.

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[1] Actual flight hours

[2] Cold proof loading test (CPLT) is a periodic proof loading testing program performed on the F-111 structure in a special facility to confirm the absence of flaws above a small critical size. This then clears the aircraft for a further period of safe flight. In a CPLT the aircraft is first cooled to -40 °F (-40 °C) to embrittle the D6ac steel structure and then load cycles of $-2.4g$ and $+7.33g$ at 56° wing sweep angle, and $-3.0\,g$ and $+7.33\,g$ at 26° wing sweep angle, are applied.

Data Study

To continue in the Sole Operator environment, the RAAF identified early that a significant increase in Australian data holdings would be required. A dedicated data study team was established, with the team tasked to retrieve all appropriate data holdings from both the USAF and OEM. This is a substantial task that aims to provide a basis for the required indigenous capability to support all the aircraft systems, not just the structural aspects.

Sole Operator Program

The RAAF Aircraft Structural Integrity section (ASI-DGTA) identified that to bridge the significant gaps between the current ASI Program and the mature ASIP required in the sole operator environment, a dedicated program was required. The Sole Operator Program (SOP), which is the focus of this paper, has been established to achieve this. The SOP was established by critically reviewing all the elements of an ASIP, identifying the shortfalls in the current RAAF F-111 ASIP and forming appropriate tasks to address these shortfalls. Importantly the SOP recognises the important roles of the RAAF, DSTO and Australian industry in the ASIP.

CPLT Facility

An integral component of the RAAF F-111 SBI program is the completion of a CPLT on each aircraft at 2000 AFHR intervals. The completion of CPLT was identified as a continuing requirement through to PWD. As such, a dedicated CPLT facility has been established at RAAF Amberley to replace the USAF facility to which the RAAF previously had access. This is new CPLT facility at a cost of A$30m was commissioned in July 2001.

Bonded Panels Repair

During USAF F-111 operations, all overhauls of RAAF F-111 bonded panels were completed by the USAF at Sacramento. With the USAF F-111 retirement, the dedicated bonded panel facility has also been withdrawn, with effect 1999. Accordingly, the RAAF initiated a program to purchase and overhaul a significant number of bonded panels prior to the facility closure. This overhaul program combined with the additional supply of panels from stored USAF aircraft is aimed to address the long term requirements; however, there is a real concern that this supply will still not be sufficient to achieve PWD for all panels.

Key Structural Issues

D6ac Steel

D6ac steel is used in the highly loaded areas in the F-111 airframe. These include the wing pivot fittings, the wing carry-through box, the overwing longerons and some key fuselage frames. The material has a short critical crack length under the F-111 loads and is highly susceptible to corrosion causing pitting. It is inspected using magnetic rubber inspection (MRI) for known and inspectable crack sites and using CPLT for uninspectable sites and general global inspection.

There have been many instances of fatigue cracks detected in D6ac steel structure in RAAF and USAF service and a number of structural failures have occurred during CPLT. Key issues for D6ac steel part management are modifying known problem areas to achieve adequate durability and relieve the MRI inspection maintenance burden, making conservative allowance for crack initiation from corrosion pits, and setting the CPLT inspection interval.

Bonded Panels

Bonded panels comprise most of the internal and external panel structure of the fuselage as well as the horizontal stabilators and other control surfaces. They consist of inner and outer aluminium alloy skins with aluminium honeycomb bonded between them. The panels suffer from corrosion and disbonding, largely due to moisture ingress. Their maintenance is very expensive and one of the major contributors to the overall F-111 maintenance cost. Key issues for bonded panels are NDI, damage significance at an individual panel level and at a global structural level (multi element damage), repair limits, repair and rebuild processes and facilities and spares and replacement options.

7079 Aluminium

Most of the F-111 forward fuselage frame, beam and longeron parts are made of 7079 T651 aluminium alloy. This material is highly susceptible to stress corrosion cracking (SCC), and widespread SCC has been detected in RAAF and USAF aircraft. The key issues for SCC are prevention and control, structural significance, multi site damage, difficult access and repair complexity.

Long Wing Fatigue Substantiation

The fatigue substantiation of the RAAF long-wing models of the F-111 is not adequate. The manufacturer's tests comprised a fighter spectrum applied to a short-wing model and a benign bomber spectrum applied to a long-wing model. The RAAF requirement is more like a fighter spectrum applied to a long wing model. In addition, the manufacturer's tests did not include CPLT loading which has a profound effect on fatigue performance. For these reasons, critical service cracks which have already occurred in the wing pivot fitting and at an outer wing station, were not adequately revealed in the manufacturer's tests. The concern is that there may be other such locations in the wing which may come to light in the next 20 years service.

There is some (but less) concern for the fatigue substantiation of the fuselage. The known fatigue problems in the fuselage are in D6ac steel parts and the strategy is to improve their management to ensure safety and durability and save maintenance costs. There is more redundancy and fail safety in the fuselage structure and the highly loaded D6ac steel parts are monitored by the CPLT. The key degradation mechanisms for the fuselage are anticipated to be environmental (corrosion, SCC and bonded panels degradation).

Ageing Aircraft

The F-111 can be considered to be an aging aircraft. It's calendar age is currently 30 years and will be 50 years at retirement. It's original design life was 4,000 hours, although the manufacturer's testing to 40,000 hours provided a fatigue substantiation of 10,000 hours life. The RAAF fleet will be approaching 10,000 hours at the time of retirement. Typical aging aircraft conditions such as widespread fatigue damage may not be relevant to the F-111, but nonetheless it is appropriate to audit the fleet condition to identify any relevant concerns.

Maintenance

Maintenance is a key issue for F-111 fleet viability. The F-111 incurs twice the hourly cost to operate as the next most expensive RAAF aircraft (the F/A-18). Cost of maintenance is the key-operating cost driver, and structural maintenance is a significant proportion of it. Aside from cost, maintenance issues also have a big impact on the operational availability of a small fleet. Containing maintenance costs and times, as the aircraft ages over the next 20 years of service, is a vital requirement.

RAAF ASIP

The ASI Sole Operator Program has its roots in the fundamental principles behind Structural Integrity Management in the RAAF. These principles have been prepared from a holistic approach, which means that they are equally applicable to shared and sole operator environments. As these principles form the framework on which the requirements of the ASI Sole Operator Program is based, an initial examination of them is required.

The broad objective of RAAF ASI management is to enable air operations to be conducted within an acceptable level of risk of structural failure of aircraft to their planned withdrawal date (PWD). The attainment of the broad objected requires the following outcomes be achieved:

constraint of risk of structural failure of the aircraft to an acceptable level,
achievement of planned rates of aircraft availability,
avoidance of the unforecast cost of refurbishment, and
achievement of the PWD.

The desired outcomes provide a spring board for the generation of strategies through which these outcomes are achieved. These strategies must reflect a life cycle approach, with their application tailored to meet the requirements of the initial concept phase, acquisition phase, and in-service phase.

These strategies are implemented through the ASIP, which identifies relevant agencies, activities and resources necessary for the achievement of the RAAF airworthiness objective. From these strategies a list of ASIP management requirements fall out. These requirements represent a framework about which the ASIP is built up. These requirements are summarised as follows:

Design Support Network	design documentation
fatigue testing and analysis (including follow on testing)	structural life assessment
usage monitoring	operational loads monitoring
structural condition monitoring	structural teardown program
configuration control (structural repair and inspection records)	structural degradation and control program
management of aging aircraft	

The F-111 Sole Operator Program ensures that the F-111 ASIP satisfies the ASI management requirements such that the nominated outcomes can be achieved.

Sole Operator Program

Participants

The engineering support originally provided by the OEM (LMAero) had to be found through different organisations, preferably in-country. This was accomplished by preserving the LMAero capability in the short term (three to five years), and using that time to transition the OEM technology and engineering capability to an in-country Design Support Network (DSN) consisting of the RAAF, DSTO and industry (Aerostructures).

LMAero Tasks

At the outset of the Sole Operator Program it was decided that the best way to develop the capability in Australia that was then solely resident in the OEM (LMAero), was to send people to the US to work on F-111 tasks with the OEM staff. Seven engineers from DSTO and Aerostructures were attached to the US in stages to work on the five tasks listed below.

Task 1 - Internal Loads Model
Task 2 - Increased Scope of RAAF DADTA Study
Task 3 - Structurally Significant Items (SSI)
Task 4 - METLIFE[3] Extension Work
Task 5 - F-111C Load Equations Review

The five LMAero tasks were completed in 2000 and delivered very useful engineering reports, models and data, in addition to the capability development. Also, the LMAero DADTA software was made available to Australia for ongoing use on F-111. LMAero displayed excellent corporate citizenship in helping Australia to make this transition.

[3] METLIFE is a Lockheed Martin proprietary crack growth analysis code.

Fleet Condition Audit

In early 2000, a thorough review of the current condition of the fleet was undertaken and provided the baseline upon which improved estimates of the projected fleet condition can be made. The fleet condition audit included the collection of maintenance data and the analysis of that data with the purpose of establishing trends. Condition data was obtained from various maintenance records from 1977 to 1999 with a total of 8507 documents included in the audit, involving 875 part numbers, and leading to 7700 entries into the database. The significant damage types on the RAAF F-111 fleet were cracking (28%), corrosion (11%), disbonds (24%) and mechanical damage (19%), and 21% of all defects were listed as having multi-site damage. The condition audit database was subsequently integrated into the F-111 Structures Information System database.

Corrosion Characterisation, Prevention & Control

An important element of the F-111 SOP is research to characterise the corrosion environment of the F-111 and the locations and rate at which corrosion can be expected to develop in its airframe. Environment sensors have been placed at the flight line and in the maintenance hangar to measure the external environment, and in equipment bays in the aircraft to measure the internal environment. Eighteen months of external environment data has been collected, but the internal environment monitoring has just started.

A laboratory test program on corrosion is in progress. It has three main areas of investigation: rate of corrosion pit development in D6ac steel with simulated imperfections in coatings; hydrogen embrittlement characterisation in D6ac steel (due to brush cadmium plating or corrosion); and use of washing detergents and corrosion preventive compounds for prevention and control of stress corrosion cracking in 7079 aluminium alloy.

Databases

CDRMS Database

The RAAF have developed the Configuration Data Recovery and Management System (CDRMS) database to store all known F-111 engineering data. F-111 engineering data collected from organisations in the United States by the RAAF Data Study Team is being scanned and stored in the CDRMS. Every piece of data is indexed against configuration item (CI), which is the lowest level at which the F-111 structure is managed (from an engineering point of view). Where applicable, information is linked to part number. CDRMS is a Microsoft Sequel database with web browser user interface.

F-111 Structures Information System

The F-111 Structures Information System database was developed by Aerostructures to enable parts/component, engineering and RAAF condition data on the F-111 structure to be stored and subsequently accessed for development of repairs, modifications and for other engineering investigations. The SIS database stores parts data (part name, part number, effectivity, material, etc), engineering data (design data, load/stress, fatigue data, etc) and condition data (damage type, location, time, part number, etc). The F-111 SIS is a Microsoft Sequel database with web browser user interface (Figure 1).

AMRL Teardown Database.

The F-111 Teardown Database was developed by AMRL to store the information obtained from examination of each part removed from the F-111 teardown aircraft. Information stored in the database includes a digital photograph of each part, all NDI reports and any other test results. This database provides the ability to pictorially drill down through the structure to identify specific parts.

The database uses a Microsoft Access database but is planned to migrate to Microsoft Sequel database. Cold fusion web server software was used for the web browser interface.

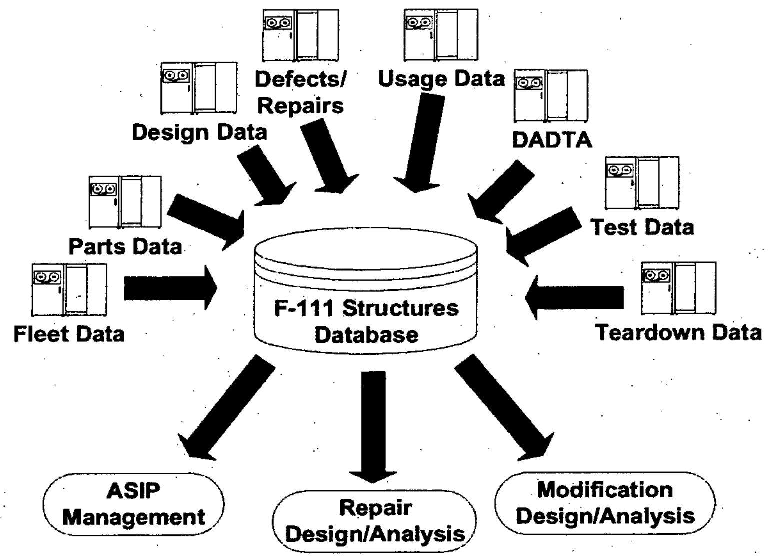


Figure 1: F-111 SIS Database

Future Direction

The CDRMS, F-111 SIS and the AMRL teardown databases have full part number identification to enable them to be cross-queried and easily linked (Figure 1). These databases provide extensive F-111 structures information, which will provide the basis for the continuing structural integrity management of the aircraft.

Fuselage Teardown

Following on from the fleet condition audit and the Significant Structural Items task at LMAero, the final leg of the strategy to identify all the critical locations in the F-111 structure was to conduct teardown inspections of a high-time fuselage and wing. A RAAF fuselage could not be spared so a retired USAF fuselage was acquired that was as similar as possible to the RAAF fuselages in configuration, usage and environmental exposure. The teardown of that fuselage is about 50% complete and involves the disassembly and visual inspection of all parts. The set of the parts deemed to be potential significant damage sites (largely based on the SSI task results) is then being subject to paint stripping, NDI (eddy current, ultrasonic, magnetic particle and X ray) and fractographic examination. The left/right symmetry of the aircraft is being used to limit the number of parts examined in detail.

The fuselage teardown involves a team of 12 fitters, technicians and fractographers and some professional supervision. It has been in progress for 18 months and will take a further 18 months to complete. Total cost is estimated to be of the order of A$5m.

Wing Test & Teardown

A RAAF wing was retired from service with 5,500 accrued flying hours and will be subjected to a full teardown inspection. Prior to the teardown, the wing is being subjected to a fatigue test to enhance any damage from service and ensure that all potential damage sites are revealed in the teardown. The total service plus test hours on the wing is currently 10,000. The test will be taken to at least 20,000 hours and possibly to 40,000 hours as time permits. The test is being done to a representative RAAF spectrum and includes the CPLT loading at the current RAAF interval.

External Loads

The external loads task at LMAero showed that the LMAero load equations for the F-111 were soundly based on flight test data to give accurate load components at a set of wing and fuselage reference stations. Follow-on work in DSTO is a re-processing of the LMAero flight test data to cover the full RAAF F-111 flight envelope. Also, detailed pressure distributions are being developed by CFD analysis to produce a full-field picture of the external loads. Automated software has been developed to pull this loads information together as input to the FE internal loads model of the airframe.

Finite Element Modelling

Internal Loads Model

The deliverable from one of the LMAero tasks was an FE Internal Loads Model (ILM) of the F-111C airframe. The model comprises 305,000 elements and 1.8 million degrees of freedom and runs in NASTRAN. Unfortunately, it was found there was little strain data in existence to validate this model, so a full-scale strain survey is to be conducted on a RAAF F-111 in the CPLT facility. The test aircraft is currently being instrumented with about 700 strain gauge elements. The ILM will be correlated with the strain data and adjusted as necessary. Then, in conjunction with the automated external loads input, it will comprise a virtual turnkey system to plug in a flight condition and determine the internal loads in the structure, which can be input as boundary conditions to a fine-grid sub-structure stress model.

The ILM will provide a key capability on which all future DADTA work and repair and modification design will be based. The complete external loads and calibrated ILM capability comes at a cost of about A$5m, but is deemed to be a very worthwhile investment.

Fine-Grid FE Models

Fine-grid FE models are currently being developed for a number of known problem D6ac steel parts in the F-111 fuselage. These are the 496 nacelle former frame, the 770 bulkhead and the overwing longerons. When loads for these models are available from the calibrated ILM, accurate stresses will be calculated in the parts for input to a fresh DADTA. Revised modification actions and inspection intervals should result in savings in future maintenance costs.

F1/F2 Fuel Tanks (Stress Corrosion Cracking)

A sub-structure FE model of the F1/F2 fuel tank area of the forward fuselage is under construction. This model will be used to evaluate the structural significance of widespread stress corrosion cracking. The fuselage teardown data and compiled data from USAF and RAAF maintenance records will be used to identify in detail all the SCC locations. Multi site damage scenarios will be investigated. Economic repair designs will be developed using this model in conjunction with local detailed FE stress models. It is envisaged that a major inspection and refurbishment of the F-111 forward fuselage will be undertaken as a one-off fix to the SCC problem. There is a large coupon test program in progress to characterise SCC in 7079 aluminium and develop prevention and control measures. These will be applied during the refurbishment program.

DADTA Capability

In the past, DADTAs of the F-111 have been performed by the OEM for the RAAF. A significant element of the Sole Operator Program has been to transfer that capability to Australia, firstly in DSTO and then transitioned to industry (Aerostructures). Two of the LMAero tasks were aimed at DADTA capability transfer, and the LMAero DADTA software has been made available to Australia for ongoing use on F-111.

In addition to acquiring the LMAero DADTA capability, DSTO has worked collaboratively with LMAero to further develop the capability. Research areas have been multi site crack initiation and coalescence and crack growth through notch plasticity fields, and the results have been coded into the LMAero DADTA software.

Corrosion Modelling

Aside from the SCC problem, the main corrosion concern for the F-111 is for pitting corrosion to initiate fatigue cracks, and D6ac steel is the material of most concern. The experimental work to characterise the rate of corrosion pit development has been mentioned. Another large experimental program is to establish the equivalent crack size (ECS) of a corrosion pit in D6ac steel. Corrosion pits of various depths were induced in test coupons which were then subjected to both constant amplitude and representative spectrum fatigue loading to a range of stress levels. The corrosion pits were also measured microscopically. Good results have been obtained from this work to establish a correlation between a corrosion pit morphology metric (depth × aspect ratio) and ECS. The next stage is to integrate the corrosion pitting rates and ECS into a crack growth analysis to develop a DADTA covering the scenario of fatigue induced by corrosion.

Bonded Panels

The main issues with bonded panels are their maintenance cost and whether the RAAF has enough spares to last to 2020. The research on developing better NDI techniques, understanding the impact of damage on strength, understanding the residual strength of aged but seemingly undamaged panels and developing better repair methods will save unnecessary maintenance and reduce necessary maintenance costs. The program to develop technology for cost effective substitution of composite material panels (described below) will mitigate against any shortfall in spares.

NDI Research

Some F-111-specific NDI research is in progress to refine techniques for bonded honeycomb panels. The options being investigated are through-transmission ultrasonics, thermography and high resolution digitisation of X rays. A large field trial has been conducted to characterise the probability of detection of magnetic rubber inspection because of its key impact on inspection intervals for D6ac steel. Specimens were cracked in the laboratory and sent to RAAF NDI technicians to inspect. The results have been analysed but have flagged the need to gather some further trials data to resolve some anomalies.

Risk Analysis

DSTO is currently building its capability to perform risk analyses. It is planned to carry out a risk analysis of the F-111 once the data from the teardown inspections is available. The aim will be to determine any appropriate adjustment of DADTA inspection intervals to allow for widespread flaws and preserve acceptable risk-per-flight levels.

Life Extension

Some life extension measures have already been taken for the F-111 to deal with known life-limiting issues. Two of them are described in detail below. They have been very successful and have the potential for more general application.

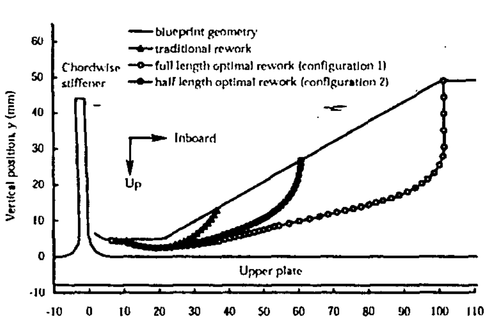
Wing Pivot Fitting Optimisation

The wing pivot fitting (WPF) is a primary structural component in the F-111 wing and has been the site of fatigue cracking in service and structural failures during cold proof load testing (CPLT). It is essentially a box structure with integrally forged stiffeners that transmits concentrated wing loads into the wing carry through box through a pivot pin. The main locations at which cracks have occurred are stress concentrating geometric features in the WPF upper plate stiffeners, known as stiffener runouts (SROs) and fuel flow vent holes (FFVHs). Typical blueprint geometries, and associated elastic stresses, at idealised CPLT loading, are shown in Figures 2 and 3, for the SROs and FFVHs. The unusual occurrence of fatigue cracking at these features in the upper plate of the wing (where the in-service flight loading is compression dominated), is attributed to the presence of residual tensile stresses which are caused by localised compresive material yielding during CPLT. Such fatigue cracks jeopardise the structural integrity of the wing and must be strictly managed in service. This imposes a costly maintenance burden. Also, the aircraft availability is reduced and at current estimated crack growth rates the planned withdrawal date of 2020 may not be achieved. Hence, any measure that allows extension of this interval can potentially produce significant benefits to the RAAF.

Historically, such critical stress concentrators have been reworked to remove the damaged material, where the rework shapes consist of circular arcs and/or straight-line segments. The design of these 'traditional' reworks has typically been undertaken using trial-and-error finite element (FE) analyses. While such traditional shapes, as shown in Figures 2 and 3, provide for crack removal, typically they do not provide significant reductions in stress concentrations, and hence further cracking usually occurs.

Hence, in the present work, precise free-form optimal shapes are determined using a finite-element-based gradientless shape optimisation procedure that has been developed in AED over recent years [2-6]. For the F-111 application, these optimal rework shapes were developed using a two stage method, where preliminary work was carried out using fully automated 2D FE optimisation analyses, with subsequent refinement being completed in a semi-automated manner using a complex and large scale 3D FE model, [7, 8]. Here the objective has been to minimise the peak compressive stresses during CPLT, which would therefore also minimise the resultant residual tensile stresses. As indicated in Figures 2 and 3, the optimal shapes typically provide a predicted 30% – 40% reduction in peak compressive elastic stresses (at the critical locations of approximately; x = 28 mm for the SROs and θ = 320 degrees for FFVHs) as compared to the traditional rework shapes. It can also be seen that the reductions are about 50% as compared to the blueprint geometries. A number of important issues have been addressed in the present practical problem, including: reduction of multiple stress peaks around the hole boundaries (both tensile and compressive); use of higher-order finite elements for efficient robust stress prediction; accounting for the effect of size constraints on the optimal shapes; and assessing the robustness [9] of the idealised optimal shapes to perturbations away from idealised conditions, such as those due to potential manufacturing errors.

As part of an associated validation program, the precise shapes have been manufactured in two full-scale static test wings using an advanced electro discharge machining procedure [10]. Experimental elastic strain measurements for the optimal shapes compare very well with the FE predictions [11], (ie less than 9% error in peak strain). Further dynamic wing tests are currently underway in order to determine the damage tolerance and durability of these optimal shapes. Based on the successful results to date, fleet-wide implementation of the optimal reworks is scheduled to commence this year.



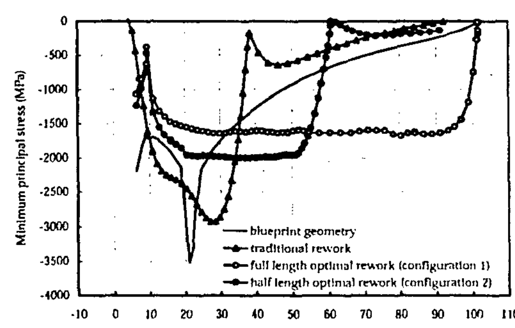


Figure 2: Comparison of blueprint, traditional and optimised rework shapes (shown inverted) and elastic boundary stress distributions at CPLT loading of +7.33g for SRO#2.

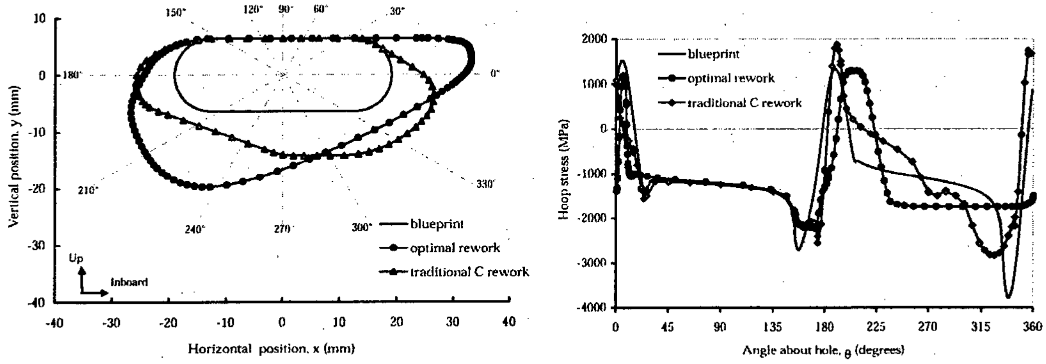
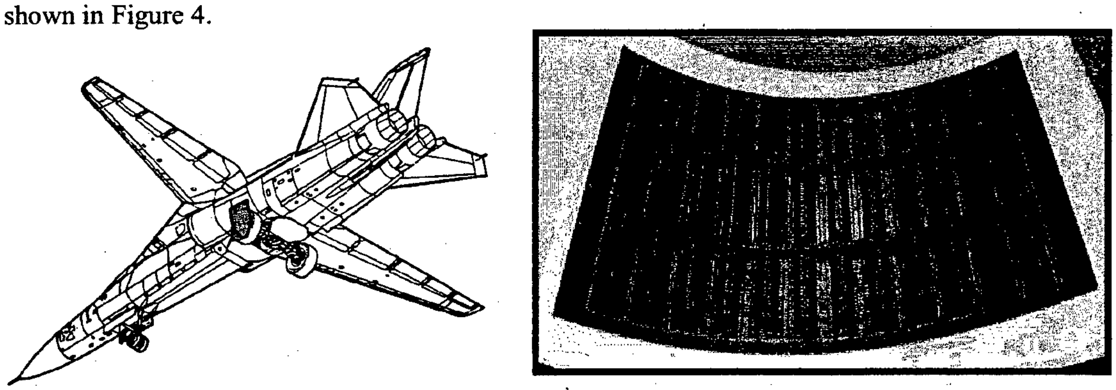


Figure 3: Comparison of blueprint, traditional C and optimised rework shapes and elastic boundary stress distributions at CPLT loading of +7.33g for FFVH 13

Bonded Panels Replacement

Each F-111 contains hundreds of bonded metallic panels, many of which require regular maintenance and/or replacement. This is very expensive. DSTO, in collaboration with the Cooperative Research Centre for Advanced Composite Structures (CRC-ACS), are therefore developing the replacement panel technology. This is a generic approach where costly-to-support metallic components, such as these panels, are replaced with more durable and cost effective composite panels. This technology is being developed and validated through the design, manufacture and certification of a demonstrator replacement for F-111 Panel 3208. The location of this panel on the aircraft and a photograph of the composite replacement, are shown in Figure 4.



(a) (b)

Figure 4: (a) Schematic diagram of F-111 showing the location of panel 3208, and (b) demonstrator replacement for Panel 3208

Design

In this work the F-111 original equipment manufacturer (OEM) stress notes were used to determine the load envelope and critical design cases for Panel 3208. Work is ongoing to develop a true reverse engineering capability, where an equivalent panel design may be determined without need for OEM data. A panel of equivalent stiffness in all modes chosen from standard composite panel solutions. The strength envelope for this replacement was superimposed on the load envelope for the metallic panel. The design was revised until the load envelope was covered fully by the strength envelope of the replacement panel. This was the preliminary panel design.

An important factor in design of the replacement panel is the panel-to-fuselage attachment. A technique for laminating thin stainless steel or titanium shims into the edge of the panels was developed, but was not needed for the trial panel because bearing stresses were low.

The effect of differences in stiffness and thermal expansion coefficient between the original panel and the preliminary panel design was then assessed. Simplified FE models of the panel and local sub-structure were generated to verify that these effects were not detrimental. For example, because of strength requirements, the shear stiffness of replacement Panel 3208 was 70 % higher than that of the original. FE models showed that this elevated the shear flow in adjacent panels by less than 5 %, which was considered acceptable.

Manufacture

A wide range of configurations was evaluated. The best compromise for cost, structural integrity and ease of manufacture was the top-hat and z stiffened construction shown in Figure 4 (b).

The first part of manufacture was to obtain the surface coordinates of the original surface. These were captured using photogrammetry because it could be performed in-situ, on a wide range of panel sizes, with a minimum of disturbance to aircraft operations.

The need to minimise tooling and curing costs led to the selection of commercially available medium temperature moulding (MTM) composite fabric. Parts laid-up with this material are initially oven-cured under vacuum at around 80 °C, released from the mould then post-cured at 180 °C as a free-standing part. This eliminates the need for an autoclave and allows the use of cheap tooling materials. The properties of these MTM composites are relatively poor under hot/wet conditions so the number of plies used in the replacement panel was increased beyond that which would be used for an autoclave curing part. The additional weight was not a problem since all-composite replacement panels will be significantly lighter than the original, 6 kg compared to 9 kg in the case of Panel 3208.

Certification

A part building block approach to certification was used, with testing performed at the coupon, sub-component and generic full-scale level. Consistent with the requirement to minimise costs, only the essential testing was included. This testing was aimed at establishing conservative design allowables for the new materials and validating the analysis/assumptions made in design.

Coupon testing was only performed to establish a conservative environmental knockdown factor for the sub-component test. The interlaminar shear test was chosen since it is known to provide the highest knockdown and is a simple test to conduct.

Representative sub-component test specimens were impacted at critical locations then tested to failure in shear and compression. This generated the static failure strain design allowables. Damage tolerance was demonstrated in a simplified program of fatigue testing of impacted sub-component specimens.

It is proposed that the final proof-of-structure be demonstrated analytically, rather than through full-scale testing as done with traditional certification approaches. Tests will be performed on instrumented flat and single curvature, close to full-scale, generic panels to demonstrate the validity of the FE models used to design the replacement panels.

This approach will be validated when an instrumented demonstrator Panel 3208 is fitted to an F-111 C aircraft and subject to a ground strain survey. The predictions made by the FE models will be compared to the strains observed during this test.

Conclusion

The SOP is currently in the fourth year of the eight year program. The majority of infrastructure development tasks, such as the establishment of the necessary testing and teardown infrastructure and database development tasks, and a considerable proportion of the data transfer tasks have now been completed. Additionally, a number of critical capabilities have been successfully transferred from Lockheed to the Australian DSN, in particular an F-111 DADTA capability now exists in Australian industry and the Internal Loads Model is now resident at DSTO.

The F-111 Sole Operator Program was a response to changed circumstances for the RAAF F-111 supportability. It forced the development of in-country capabilities. The total cost of the F-111 SOP is estimated as A$25m. Its prime purpose was to ensure continued safe operation of the RAAF F-111 fleet for the remaining 20 years of service. However, it is expected that the program will pay for itself several times over in maintenance savings, without even having to be justified in terms of delayed replacement acquisition savings. As such, it shows that for any aircraft fleet, it can be worthwhile to step back and take a fresh holistic look at its management and identify areas where research leading to enhanced support capability can have a significant pay off.

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